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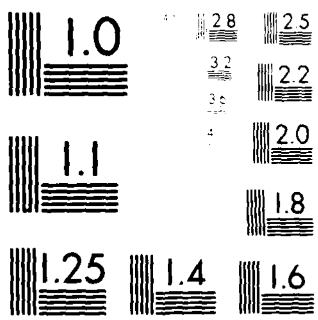

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VSC-TR-82-2

I. THE DETECTABILITY OF HIGH FREQUENCY ENERGY AT TELESEISMIC AND REGIONAL DISTANCES
II. STUDIES OF RADIATION FROM HIGH-EXPLOSIVE AND NUCLEAR CRATERING EVENTS

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I A survey of the literature on short-period seismic studies shows that seismic waves of high frequency in the 3-10 Hz range, can be observed regularly at both regional and teleseismic distances. These observations show that the low Q values proposed for the long-period seismic waves cannot be valid in the short-period band. The data indicate that, in the mantle, Q increases with frequency and may be as much as five times higher at 5-10 Hz than in the long-period band. Even with the most conservative assumptions, the level of high

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frequency amplitudes in teleseismic P waves exceeds that predicted with a constant t^*_β = 1 sec by a factor of at least 10^4 at and beyond 5 Hz.

The apparent Q_β of the lithosphere, which may be largely due to scattering by the small scale inhomogeneities in the crust, also shows an increase with frequency by as much as a factor of four within the 1-10 Hz band. This parameter controls the attenuation and the detectability of seismic waves at regional distances such as P_n, P_g, S_n and L_g.

These results indicate that deriving source diagnostics for explosions and earthquakes at both teleseismic and regional distances is possible utilizing high frequencies, and methods to do this must be developed further.

II A survey of existing data from cratering explosions reveals that there is no hard-rock transverse component digital data. The best all-around data available is that taken in Yucca Lake by Lawrence Livermore Laboratory in 1973-1974.

I THE DETECTABILITY OF HIGH FREQUENCY ENERGY AT TELESEISMIC AND REGIONAL DISTANCES

II STUDIES OF RADIATION FROM HIGH-EXPLOSIVE AND NUCLEAR CRATERING EVENTS

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INTRODUCTION

Seismic energy in the 2 to 20 Hz range has received relatively little attention in the studies of yield estimation, detection and discrimination of seismic events. There are several reasons for this.

First of all, in a threshold test ban treaty (TTBT) mostly teleseismic events are of interest and the seismic energy is small for teleseismic signals in this frequency range. Another reason is that for a long time Q in the Earth was thought to be constant and quite low, resulting in travel time to Q ratios near unity (5, 7, 8)* (this ratio is called t*) that precludes the observations of teleseismic energy in this frequency range. In addition, the best United States stations are in the West and in Alaska where Q is low. It appears, however, in the light of recent research that Q may vary with frequency and may also be considerably higher than previously assumed for the types of paths that are of prime interest in detection and discrimination studies, the paths involving the upper mantle under shields (21, 22, 23, 24, 29, 31, 36, 37, 56, 60, 61, 69, 85, 88). Such higher Q in the upper mantle makes the observation of high frequency energy possible at teleseismic distances at least in the 2 to 5 Hz range. It is therefore important to exploit any information that the high frequency signals contain about the seismic source. Moreover, it is important to know, both from a detection and a discrimination point of view, how Q varies in the mantle as a function of tectonic history and crust-upper mantle structure. Knowledge of mantle Q is important for yield estimation since Q can cause variations of seismic wave amplitudes, and low Q may make some spectral discriminants ineffective.

At regional distances, in the framework of a possible complete test ban (CTBT) monitoring problem, crustal Q becomes important for the detectability of events. Small or decoupled larger events excite predominantly high frequency energy due to the higher corner frequency or the decoupling mechanism itself and the detectability of such events is primarily determined by the crustal Q they encounter along the path. Because most of the energy at regional distances is associated with phases that propagate primarily in the

* Numbers in parentheses refer to the list of selected references, unless otherwise identified.

crust, mantle Q enters into the picture through phases like P_n and S_n that propagate at least partially in the uppermost part of the mantle. In any case, knowledge of the propagation characteristics of high frequency seismic waves is, at best, sketchy at this time and thus needs to be improved.

Since there is a wide body of existing knowledge of high frequency propagation characteristics, instead of simply cataloguing reports of high frequency observations, we shall discuss the literature in terms of the tectonic framework that determines the efficiency of high frequency propagation. At teleseismic distances the presence or absence of high frequency energy is primarily determined by the upper mantle Q structure. In general, low upper mantle Q is associated with the presence of a low velocity layer in the upper mantle. At regional distances the apparent crustal Q appears to be the dominant factor. It is not clear at this time how much of this parameter is associated with the intrinsic attenuation in shear and how much of it is due to scattering of crustal S waves because of lateral inhomogeneities.
In any case, the efficiency of high frequency energy propagation in the crust appears to be correlated with the apparent crustal Q.

It is not practical to discuss high frequency propagation in the earth in general terms without any reference to the particular region studied. For practical application of any yield estimation and discrimination methods based on high frequency observations, the relevant parameters' Q values must be known for the paths studied, i.e., the geographical and frequency dependence of Q must be known. This report is a brief summary of the findings of a literature search we have conducted to assess the present state of knowledge both of the characteristics of high frequency seismic energy and of the factors that determine the efficiency of its generation and propagation. In performing the literature study, it was found to be impractical to quote just the abstracts of papers since few of the references are studies of high frequency energy *per se*. On the contrary, references to observations of high frequency seismic energy are often found in studies with a different stated purpose, such as works on seismicity, global tectonics and plate motion, low Q regions behind island arcs and the like. Nevertheless, there are numerous reports of observations of high frequency seismic energy in quite a variety of geophysical environments, and these seem to justify further seismic studies in this frequency range.

This review is a condensed summary of the available literature, and it discusses the general characteristics of high frequency propagation in the Earth in terms of the global tectonic setting, instead of compiling the details available in the literature. We are of the opinion that a detailed compilation would be less useful, and it would also be extremely difficult to assemble. The amount of detail would be so large that the reader would be quickly overwhelmed by it. References to observations of high frequency seismic waves are scattered throughout a large number of papers. I believe we have succeeded in locating the most important contributions. The most relevant references are cited in the text.

This report is not meant to be a complete and exhaustive summary of the present knowledge of high frequency energy in seismic waves and the regional variations of seismic wave attenuation in the short-period band. The intended purpose of this note is to outline the general picture, the tectonic settings, the possible frequency dependence and the limits of detectability of high frequency energy. It may appear to the reader that some of the tectonic environments discussed in this report are not of interest in a CTB monitoring situation since none of the test areas are located in such regions. Knowledge of the transmission characteristics for high frequency waves is still important because many seismic stations used in monitoring are located in such environments. It seems from the available evidence that the detectability of 3 to 10 Hz energy in seismic waves correlates with the attenuation patterns of 1 to 3 Hz waves over similar paths because spectral analyses of data showing visual energy usually reveal 3 to 5 Hz energy as well in P-waves and observations of 1 Hz energy in teleseismic short-period S also correlates regionally with notable enrichment of 4 Hz energy in P (26, 27). Our search of the literature did not show any exceptions to this rule. It appears therefore that the numerous studies of 1 to 3 Hz attenuation using mostly visual observations on standard short-period recordings are relevant and can be used to predict the detectability of 3 to 10 Hz energy in various regions.

OBSERVATIONS OF HIGH FREQUENCY SEISMIC ENERGY AT TELESEISMIC DISTANCES

Although reports of observations of high frequency energy in teleseismic body waves appear repeatedly from the early days of seismology, development in this field was considerably hindered by the lack of suitable recording systems and the wide use of the WWSSN film data, which does not allow for digital conversion and has an extremely poor time resolution on the recorded traces. The seismometers themselves, on the other hand, were more advanced than the recording systems and, coupled with digital or analog recording systems, were capable of recording seismic signal energy in the 2 to 10 Hz range, above the system and background seismic noise. With the increasing use of such systems and networks and arrays utilizing them, reports of signal spectra containing significant energy in the high frequency range became more frequent. A significant proportion of such results were produced in the 1960's by the LRSM and VELA arrays, LASA, NORSAR, as well as the British arrays. More recent data is available from the SDCS and SRO systems. Reports of high frequency observations have been published using special systems such as those in Japan that record seismic signals in the 1 to 10 Hz band (94, 95, 96). The wide use of WWSSN data did more to retard the advance of high frequency seismology than to advance it. Since the highest visible frequency in such data is about 2 to 3 Hz, the impression was created in the minds of many seismologists that no significant seismic energy is present beyond these frequencies in teleseismic signals (5, 7, 8). Besides, at teleseismic distances the dominant frequency is about 1 Hz for P waves due to Q effects and the dominance of analyzed signals by large events for which the corner frequency is below 1 Hz. Moreover, many seismologists relied almost solely on the time domain inspection of records and on comparisons with synthetic seismograms. Due to the system response, this approach de-emphasizes the importance of high frequency information in the data. Detection of 3 to 6 Hz energy requires digital filtering or spectral analysis of teleseismic data and cannot easily be detected visually (46) on the standard instrumental records. It is not surprising therefore that authors not using suitable analysis techniques or data came up with negative results concerning the existence of high frequency energy in seismic signals.

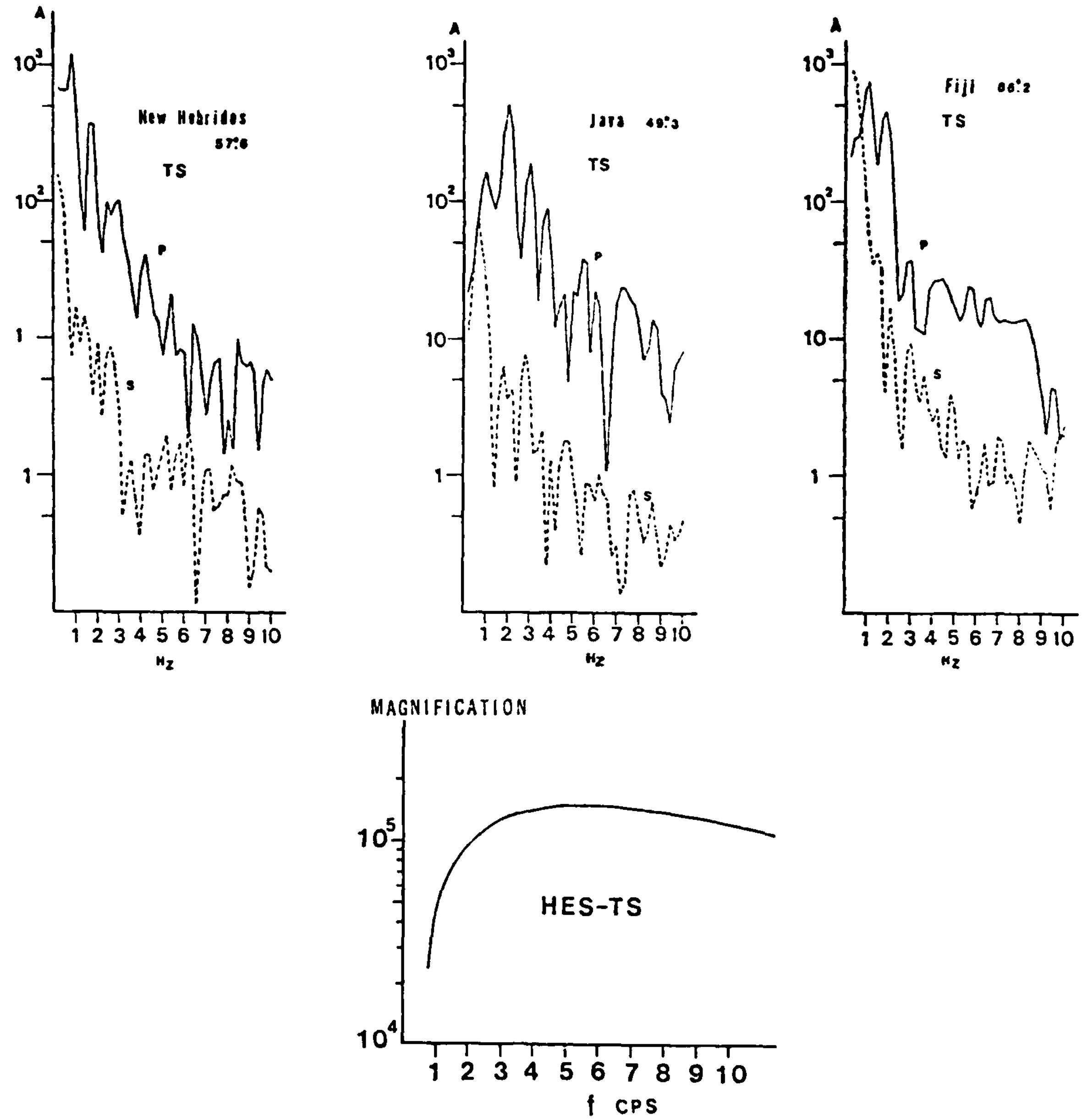

Figure 1. P and S wave spectra for several deep events observed at Mt. Tsukuba, Japan (after Takano, 1971). Although the noise levels are not given, they must be below the spectra levels of S, that incidentally, were also observed visually. The P spectra show significant signal energy to 10 Hz. The equivalent constant t_p^* is ~ .20 assuming a flat source spectrum which is quite unreasonable for events of this magnitude $m_b > 5$. A more reasonable spectrum should fall off with frequency as ω^{-2} resulting in a $t_p^* = .08$. The response of the system used is shown at the bottom; it has a nearly flat response between 2-10 Hz. Both t_p^* values given above are considerably below the values claimed for the long-period band (of the order of .8) for deep events. The value of .8 would cause a discrepancy in the ratio of 2 to 8 Hz amplitudes of at least 8×10^4 relative to those observed.

In spite of the limitations of WWSSN data and the limitations of visual analysis, a considerable amount of research was done that indicated large lateral variations of mantle Q in the upper mantle. Although the estimates of Q were largely obtained by comparing visually the frequency contents and amplitudes of signals that, as we pointed out above, do not go beyond 2 to 3 Hz, the results have important implications for signals at higher frequencies since the lateral variations of Q govern the detectability of high frequency energy 3 to 6 Hz. In the following, we shall summarize the main features of high frequency propagation to teleseismic distances in various tectonic environments of the world.

Shield and Stable Platforms

These regions are characterized by the absence of low velocity-low Q layer in the upper mantle and this implies effective propagation of high frequency energy through the mantle. This is evidenced by the detectable 2 Hz energy in short-period S waves from deep earthquakes observed in these regions and the frequent observation of 5 to 6 Hz energy in P waves (Figures 2 and 3) teleseismic signals (9, 27, 30, 31, 36, 52, 69, 95). The high upper mantle Q is reflected in positive magnitude anomalies associated with such regions worldwide (16, 19, 23, 28, 53).

Tectonic Regions and Rift Zones

Regions falling into this category, especially the rift zones, are characterized by the reduction or complete elimination of high frequency energy (1 to 2 Hz in teleseismic S from deep events and 4 to 6 Hz in (Figure 4) teleseismic P waves due to losses in the mantle (23, 27, 31, 36, 69). The same regions also generally have negative amplitude anomalies (71).

Island Arcs

Island arcs exhibit an extremely complex pattern in the lateral distribution of mantle Q that also varies among the various island arc regions. A characteristic and important feature in many island arc regions is a low Q region behind the subduction zone that causes attenuation of body waves. The downgoing slab itself has a high Q that can facilitate the detection of high frequency waves if the waves travel downward through it (10, 11, 12, 13, 14, 18, 39, 45, 63, 64, 66, 74, 77)(Figures 5 and 6).

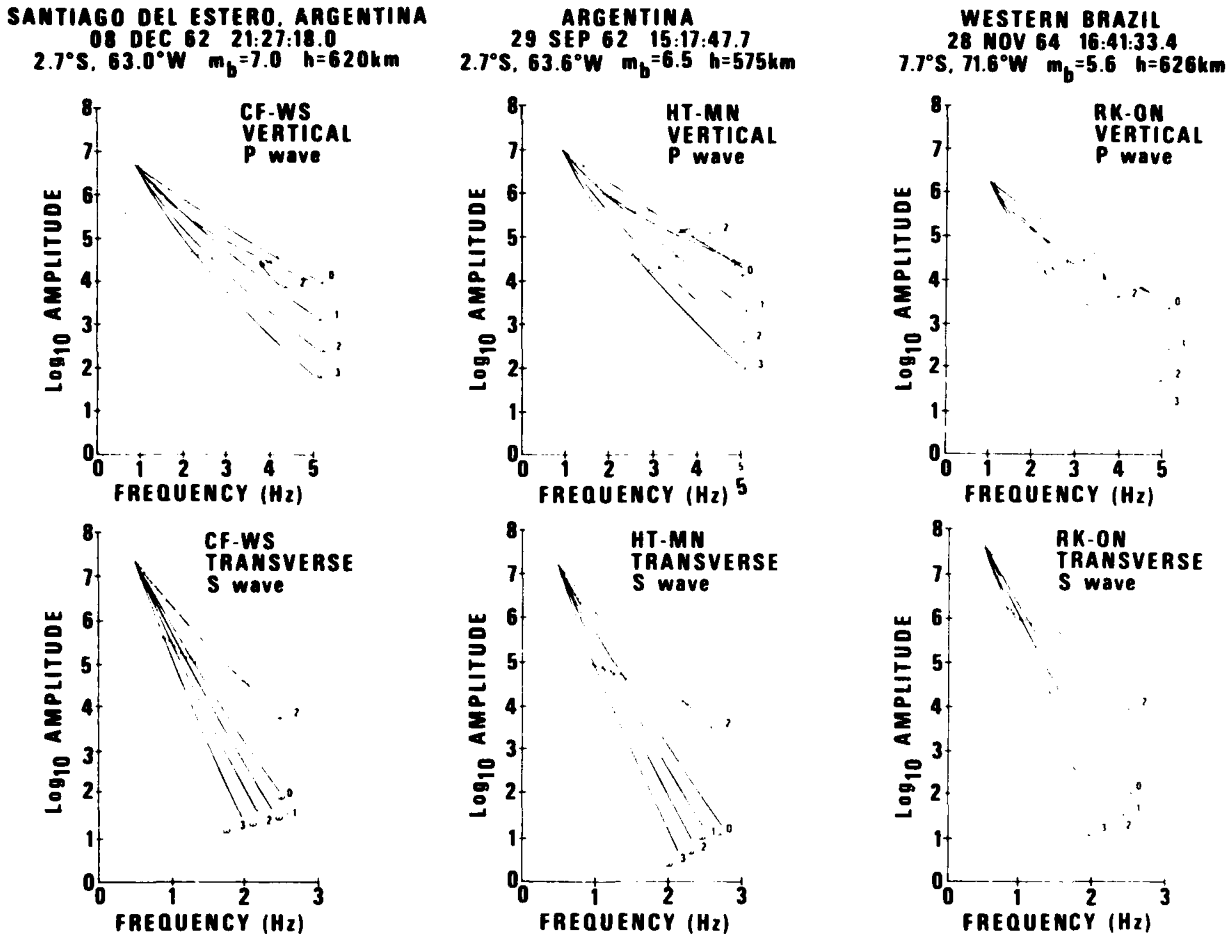

Figure 2. Instrument corrected P and S wave spectra observed at hard rock sites in the southern part of the Canadian shield. Lower curves show the spectra of noise background preceding the arrival of the respective phases. The P spectra are above the background noise up to 5 Hz and the S wave spectra up to at least 2 Hz. The solid curves show the expected falloff of spectra assuming rates of source spectrum decrease ω^{-n} for $t_s^* = .5$ and $t_s^* = 2$ sec; one half the value for shallow events commonly used in the long-period band (to allow for source depth). Since the events in question are large, ω^{-2} characterize the most likely source function. The discrepancy between the observed and predicted spectra with ω^{-2} exceeds two orders of magnitude at the high frequency end of both P and S waves. The dashed lines superposed on the spectra correspond to $t_p^* = .2$ and $t_s^* = .8$ assuming a ω^{-2} falloff in the source spectra. Even at these low t* values the spectra do not fit well and lower attenuation is indicated. The spectra clearly demonstrate that the discrepancy is prevalent even in the vicinity of 1 Hz. This figure shows that the high t* values frequently used in the long-period band are certainly not valid for short-period data. Note also that even if one assumes an unlikely ω^0, flat source spectrum, a large discrepancy still exists. These spectra shown are typical of many deep events observed in the north central U.S. and indicate high Q in the mantle under the shield.

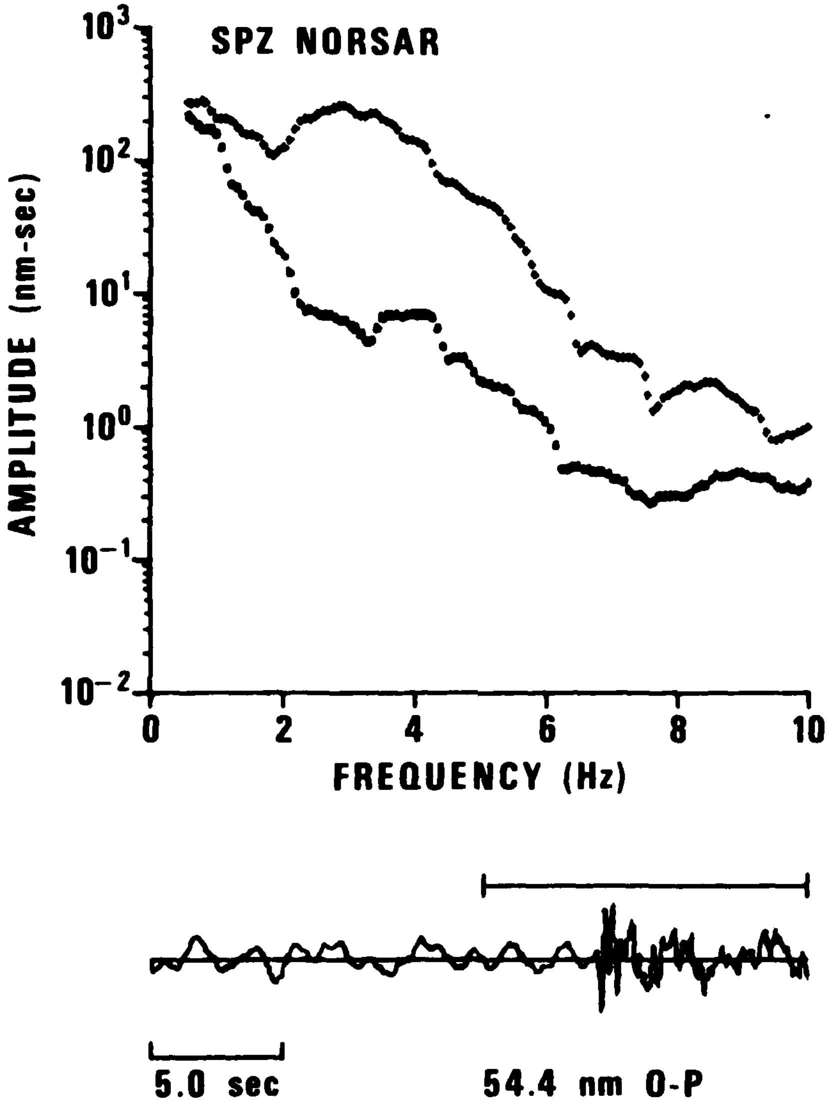

Figure 3. Amplitude spectrum of a suspected nuclear explosion recorded at NORSAR at a distance of 23.4° in western Russia. The spectrum shows significant signal energy above the noise level up to 10 Hz. This is an upper mantle arrival indicating a high Q mantle under the path.

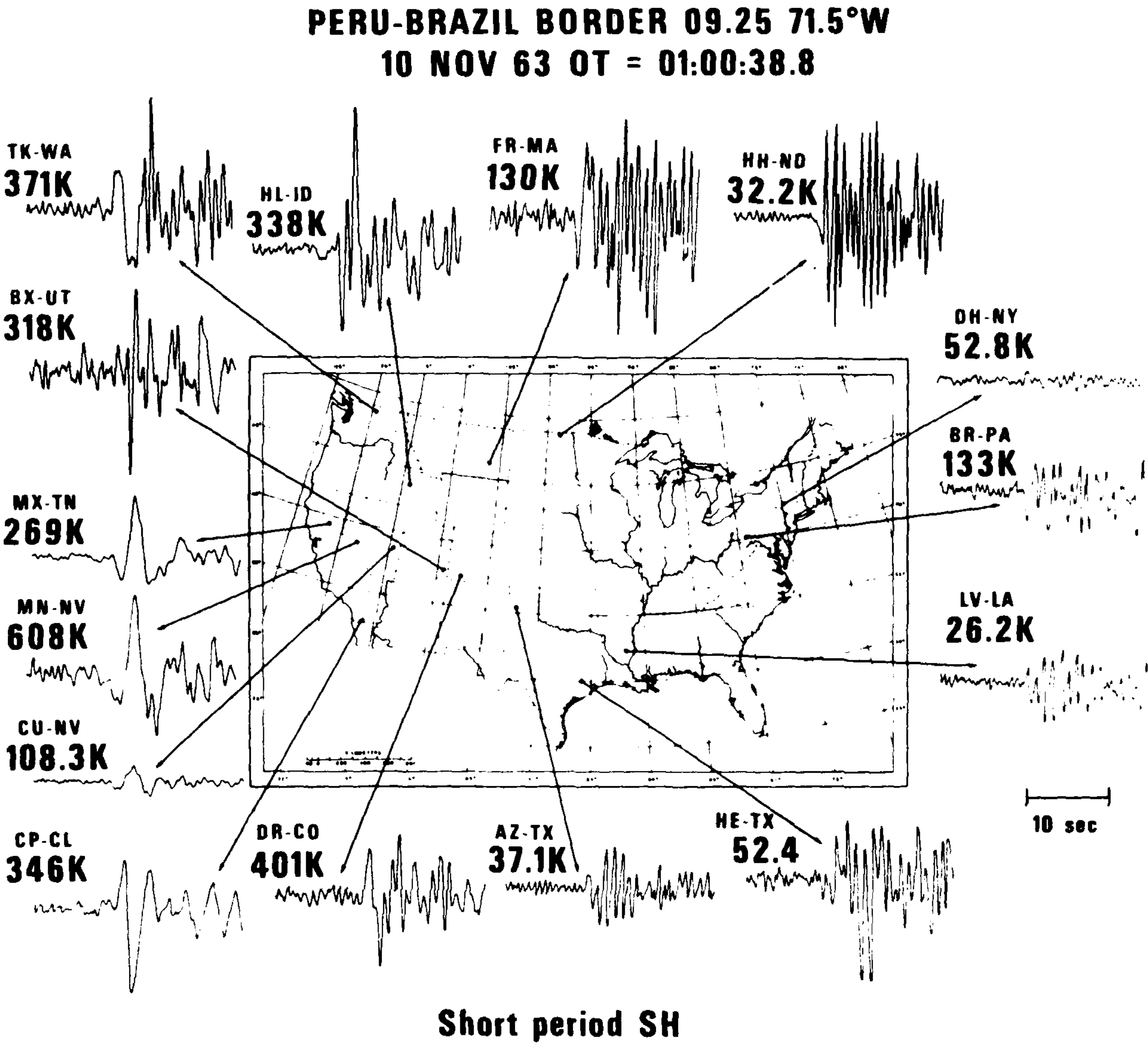

Figure 4. Film tracings of short-period S waves from a deep earthquake on the Peru-Brazil border (9.3°S, 71.5°W) on November 10, 1963 at 01:00:38.8. Pointers show the location of recording LRSM stations on the map. Since one of the perpendicular horizontal components of the LRSM stations is oriented towards NTS, the tracings were done on the component closest to the transverse direction (SH) to the event. The differences in frequency contents and amplitudes are typical for the United States and are caused by lateral variations of mantle Q.

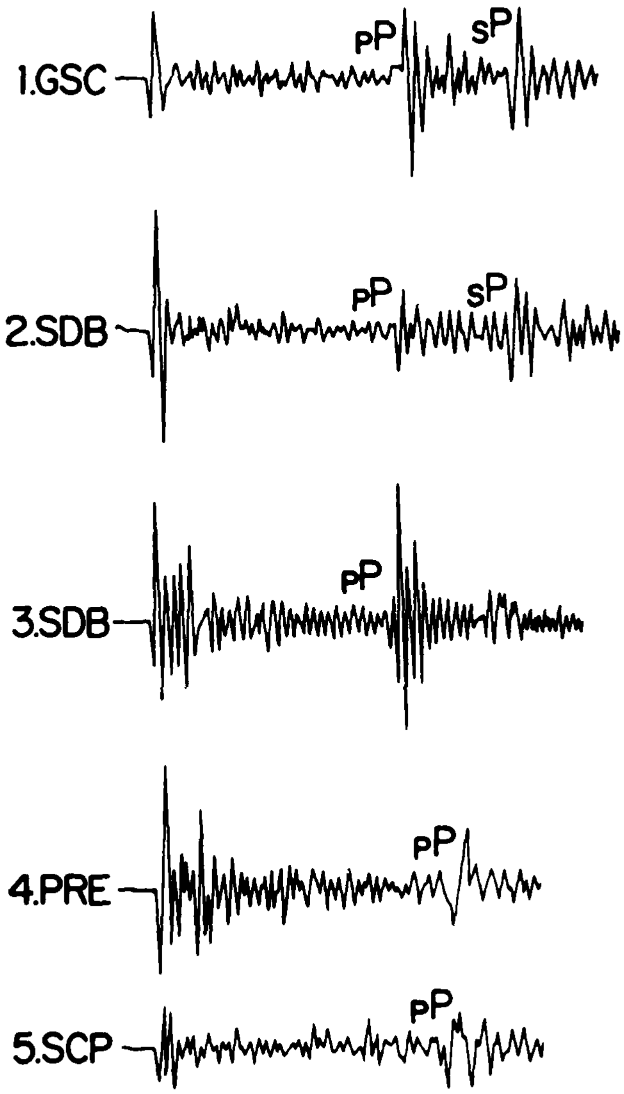

Figure 5. Recordings showing the effect of upper mantle Q on surface reflections from deep events. Surface reflections that traveled through high Q upper mantle show clear high frequency pP and sP phases (traces 1, 2, 3); traces that show small low-frequency pP and no sP indicate low Q upper mantle above the source (traces 4, 5) (after Barazangi et al., 1975).

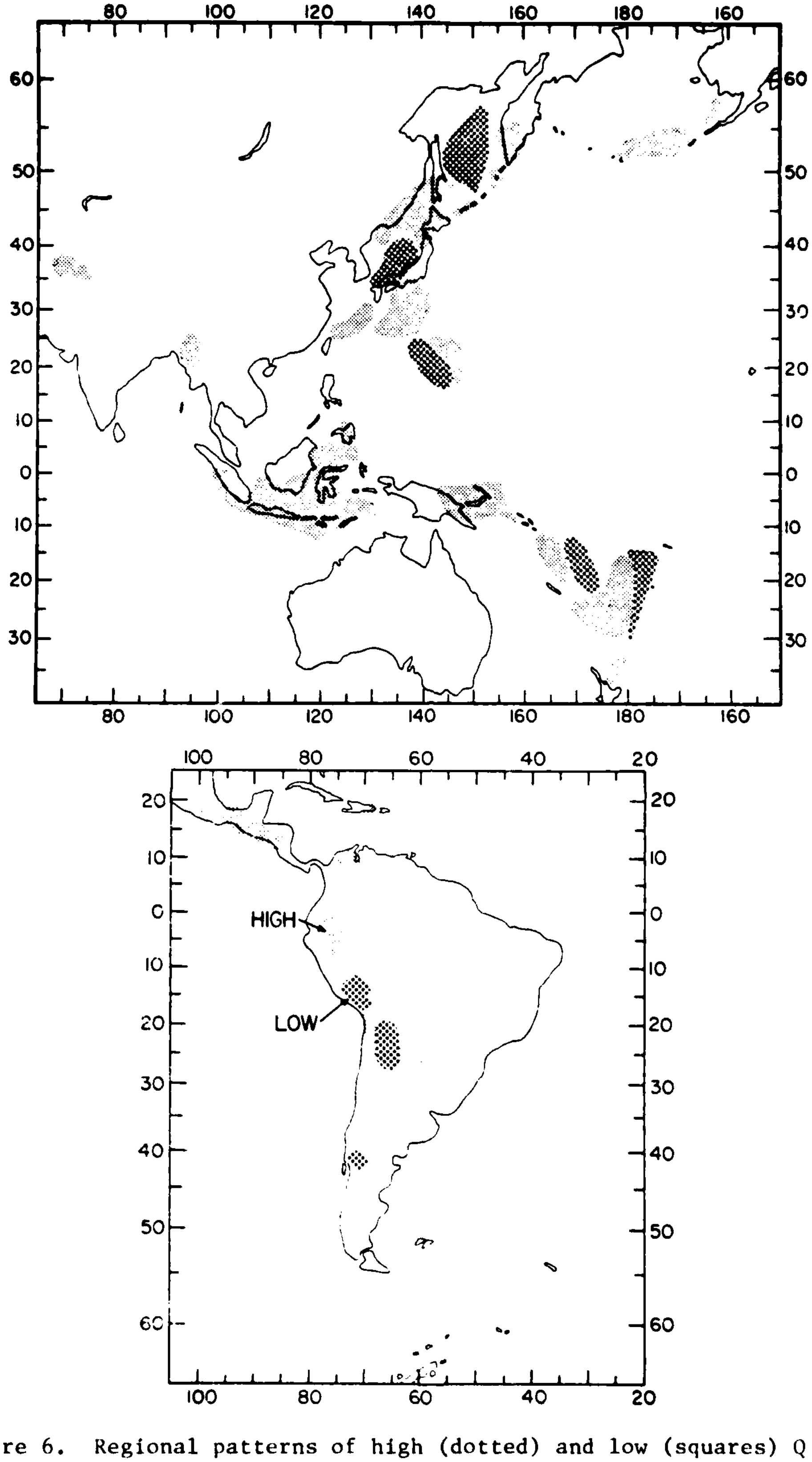

Figure 6. Regional patterns of high (dotted) and low (squares) Q upper mantle as indicated from surface reflections from deep events (after Barazangi et al., 1975).

Mid-Ocean Ridges

Mid-ocean ridges are underlain by a low Q-low velocity mantle material that, according to most evidence, severely attenuates seismic waves.

Oceans

Depending on the age of the ocean, the attenuation properties in the mantle change considerably but data in the 3 to 6 Hz range are extremely scarce. It is likely that the older oceans are underlain by mantle with higher average Q than the new oceans near ridges. This may be due only to the varying lithospheric thickness. The 3 to 6 Hz frequency range is practically unexplored due to the past lack of interest in the problem and the low seismicity of such regions (85, 86).

Miscellaneous Other Regions

Several other regions not falling into the above categories have been studied (18, 45, 68, 80, 92). The mantle under the Tibetan Plateau is thought to be underlain by low Q mantle. Several regions under western South America, a subducting region but not an island arc, have been found to have low Q regions in the upper mantle.

It appears from the discussion above that it is not possible to make general statements about the detectability of high frequency energy, and through it the detectability and discrimination of small and/or decoupled explosions without some knowledge of the Q structure of the upper mantle. Clearly, events located over low Q mantle will be harder to detect and some discrimination methods based on seismic wave spectra will break down.

OBSERVATIONS OF HIGH FREQUENCY ENERGY AT NEAR AND REGIONAL DISTANCES

Seismic energy at near and regional distances is primarily contained in phases that propagate in the crust and the uppermost part of the mantle. While the apparent Q in the mantle is associated with intrinsic Q caused by physical mechanisms that relate to the temperature effects on the mantle materials, losses in the crust may not be caused by such mechanisms at all. Since the Earth's crust is laterally inhomogeneous and regional phases propagate in the crust to large distances, a great portion, if not all, of the losses may be caused by scattering of the elastic waves by inhomogeneities (1, 2, 3, 57, 97). Intrinsic Q may also play a significant role, but present views on the subject vary. Similarly to the mantle intrinsic Q, the losses in the crust are more severe for shear waves but the relationship between shear wave and compressional wave Q may not be the same in detail.

At regional distances the following phases play an important role:

P_n propagates primarily in the uppermost part of the mantle. It can be regarded as a superposition of higher Rayleigh modes that are primarily controlled by the upper mantle lid.

S_n is an analog of P_n involving propagation of higher mode Rayleigh and Love modes (90).

P_g, originally coined to designate a head wave at the granite-sediment interface, is primarily used for a superposition of higher Rayleigh modes with a group velocity of about 6 km/sec observed at regional distances in some areas. In other areas, it is missing.

L_g is a superposition of higher Love and Rayleigh modes propagating at approximately 3.7 to 3.5 km/sec and constitutes a prominent wavetrain at about 1 Hz on standard short-period seismograms.

Oceanic P_n and S_n are analogous to their continental counterparts, but are different in their characteristics and frequency content.

Based on the available evidence, it is difficult to make meaningful general statements on the detectability of high frequency energy at regional distances. It appears from the literature review that in many regions, 10 Hz energy can be detected at distances of 500 km and lower frequencies at greater distances (32, 38, 106). At distances of the order of a few hundred kilometers, 20 Hz energy has been observed routinely with suitable high frequency instrumentation. The variations from region to region in the propagation efficiency of such high frequencies needs to be investigated further (32, 38, 70, 72, 76, 102, 103, 104, 105, 106).

On the other hand, studies of propagation efficiency of high frequency energy at lower frequencies in the 1 to 3 Hz range are more abundant. All the available evidence indicates that the efficiency of propagation in this range is closely related to that at higher frequencies (65, 93). From the findings of these studies, therefore, we may get some ideas about the efficiency of propagation at higher frequencies.

The efficiency of propagation, usually expressed in terms of crustal Q_β, can be measured in various ways. In the time domain, the decrease of amplitudes with epicentral distance may be measured and compared to some theoretical rate that is usually a falloff rate of an Airy phase. Alternatively, in the frequency domain r^{-1}, falloff rate with distance for energy is assumed due to geometrical spreading and the actual falloff rates as functions of frequency may be measured and an effective Q, either constant or frequency dependent, may be derived (see Figure 7). A third method based on coda measurements can also be used to derive Q. To check the scattering of Q in the crust, the coda excitation level may be measured and compared to predictions of scattering theory (42). As general results thus far the following can be stated.

<u>Shields and stable platforms</u> are generally characterized by high crustal Q, resulting in low attenuation of L_g, P_n and S_n along paths in such structures. The low attenuation is shown by all the criteria above; less falloff with distance, less loss in high frequency content, low coda excitation (4, 15, 42, 65, 93) (see Figure 8).

<u>Tectonic regions and rift zones,</u> on the other hand, are distinguished by low efficiency of propagation for all the above mentioned phases. There is a loss of high frequency content and a larger falloff rate with distance which in the case of S_n, and L_g to some degree, can become a complete extinction of the phase when propagating through such areas (40, 65). It must be noted, however, that since the various phases mentioned are controlled by different parts of the crust and upper mantle, complete correlation among the propagation characteristics of these phases cannot be expected (4, 40, 42, 65, 73, 78) (see Figures 8 and 9).

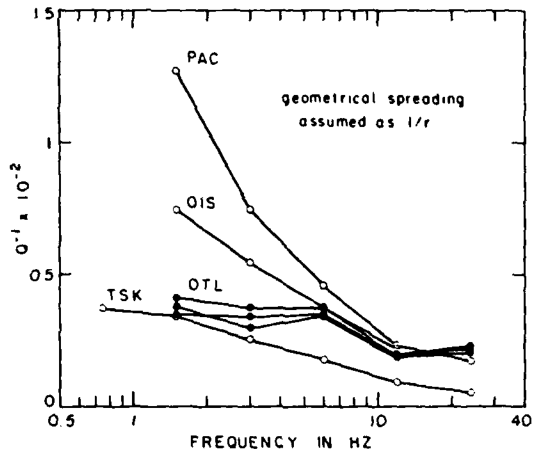

Figure 7. Q^{-1} of coda waves as a function of frequency obtained by Chouet [1976] for local earthquakes recorded in central California (PAC), western Japan (OSI), central Japan (TSK), and Island of Hawaii (OTL). the last coda shows distinctly different frequency dependence, suggesting a different attenuation mechanism than the others (after Aki, 1980).

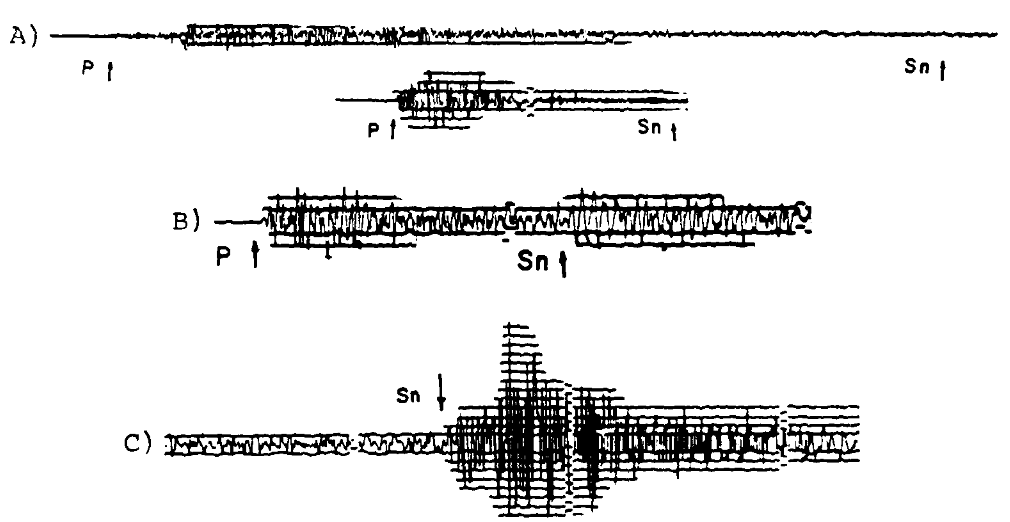

Figure 8. Examples of S_n phases observed along paths with varying efficiency of propagation. From the top to bottom:

A) Inefficient propagation with S_n missing.

B) More efficient propagation with S_n having about the same amplitudes as P and showing predominantly low-frequency characteristics.

C) Efficient propagation with a large high-frequency S_n (after Molnar and Oliver, 1969).

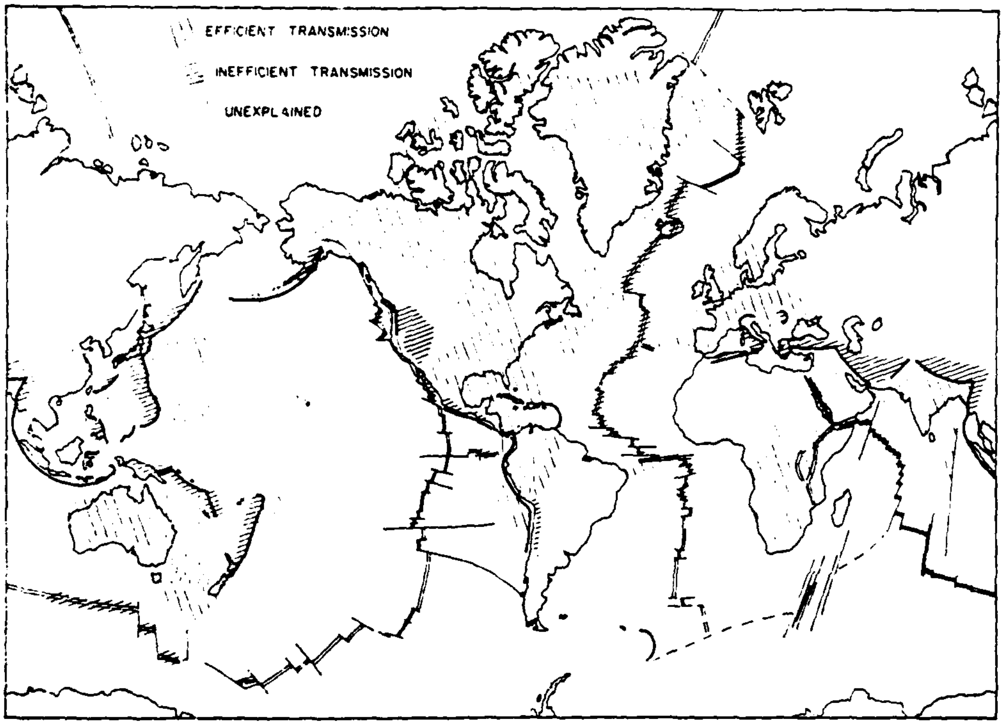

Figure 9. A summary of the efficiency for S_n propagation (after Molnar and Oliver, 1969).

Ocean ridges have been reported to block the propagation of S_n (74). L_g does not propagate through oceans (65).

Island arc regions above the dipping slabs were shown to block propagation of S_n and other high frequency phases (10, 13, 65) (see Figures 10 and 11). Oceans, on the other hand, outside ridges and arcs were shown to be extremely efficient wave guides for S_n and P_n. The frequency content of these phases is high in the 10 to 20 Hz range and the associated Q values are extremely high (98, 99, 100, 101) (see Figure 12).

Seismic Background Noise in the 3 to 20 Hz Range

All available studies of seismic background noise show decrease of noise amplitude with frequency (34, 35). This is favorable for the detection of high frequency energy from regional events, since it tends to compensate for the reduction of signal amplitude by attenuation, thereby keeping the S/N ratio from decreasing rapidly with frequency. (Installing the instrumentation in shallow boreholes does decrease the noise drastically from place to place), and stations should be placed at low noise sites for effective detection (34, 35).

The Frequency Dependence of Q in the Mantle and the Crust

Comparison of Q measurements in the short- and long-period bands reveal a contradiction that can only be reconciled by assuming an increase of Q with frequency (5, 6, 7, 8, 9, 17, 23, 26, 27, 31, 36, 52, 56, 59, 67, 69, 82, 88, 95). If constant Q is assumed, the high frequency energy observed in teleseismic body waves should be considerably below the system noise level if the low Q values determined in the long-period band are assumed to be constant. The details of such frequency dependence may be quite complex and need to be investigated further (26, 56, 85, 88). There are a large number of possibilities involving several frequency dependent attenuation mechanisms also varying as functions of depth and geographical region (26, 56, 88). Regardless of such details, there is no difficulty in reconciling such models with existing theories of anelastic dissipation in the Earth, since practically all proposed mechanisms of attenuation in the mantle are inherently frequency dependent.

Attenuation of regional crustal phases also involves a frequency dependent Q_β, which in this case, is an apparent one since it contains the effect of intrinsic anelasticity and the losses in scattering in the crust-upper

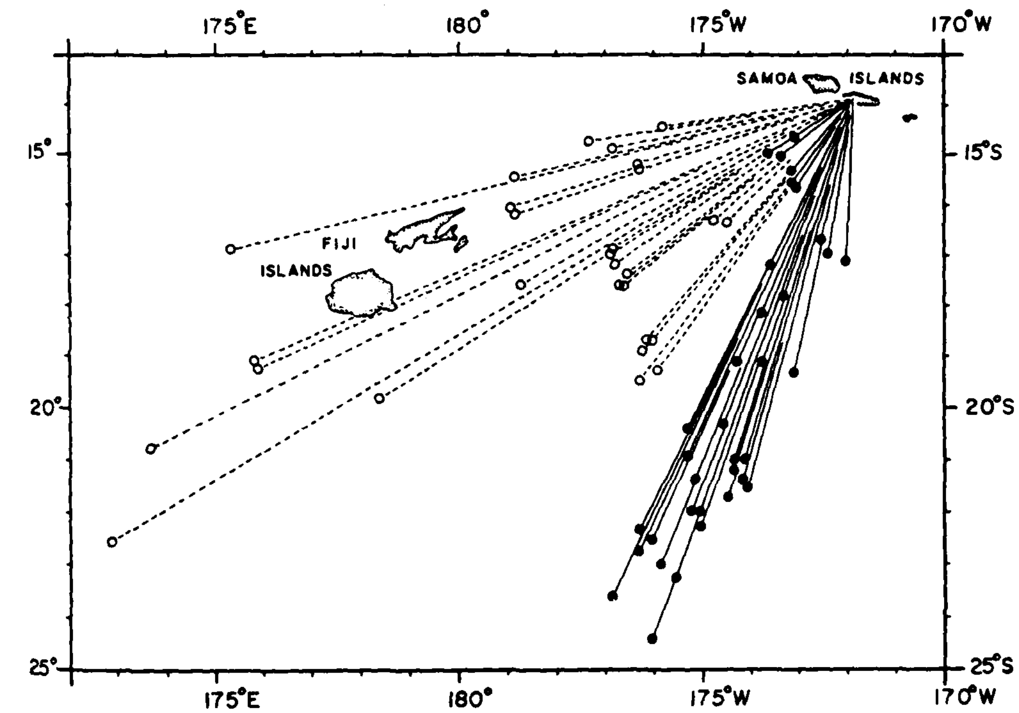

Figure 10. Regional patterns of efficient (solid lines) and inefficient (dashed lines) P_n and S_n propagation in the Fiji region (after Barazangi and Isacks, 1971).

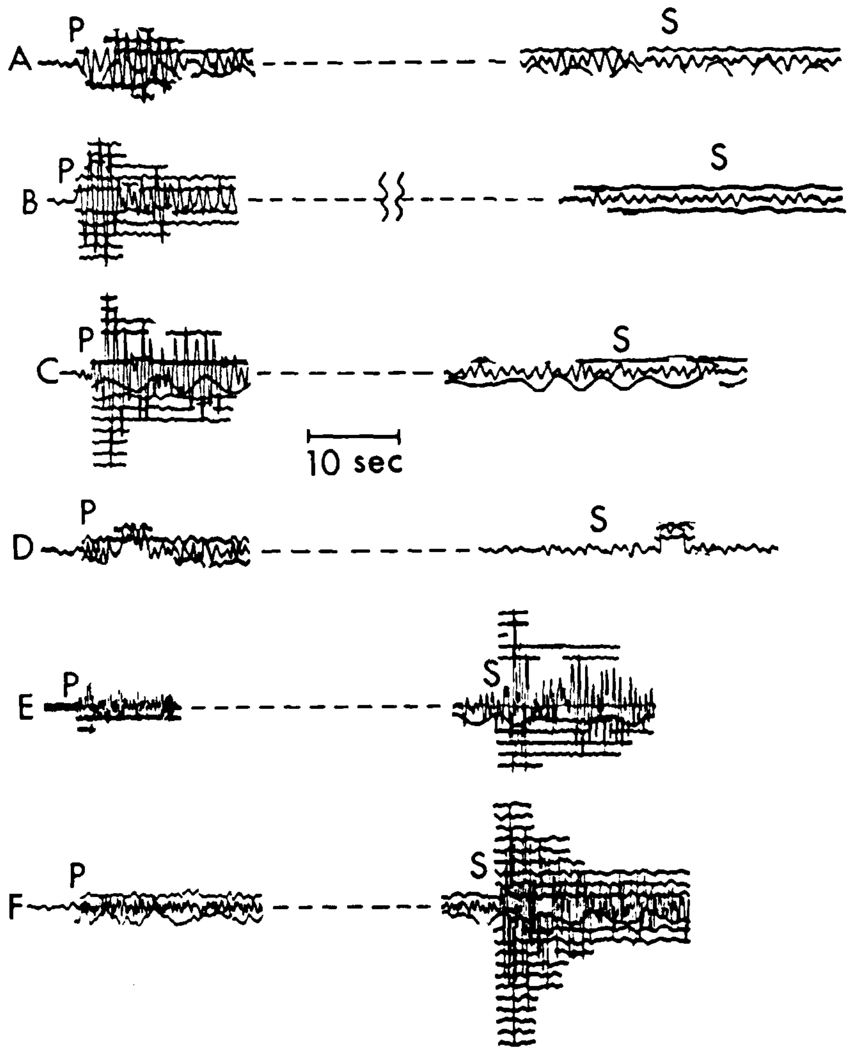

Figure 11. Examples of P_n and S_n phases from the Fiji region. In regions of low Q the S_n phase is not detectable and the P_n phases have a low-frequency character (traces A, B, C, and D). Efficient propagation is characterized by distinct high-frequency P_n and S_n (traces E and F). (NOTE: P_n and S_n are marked as P and S in this figure by Barazangi and Isacks, 1971.)

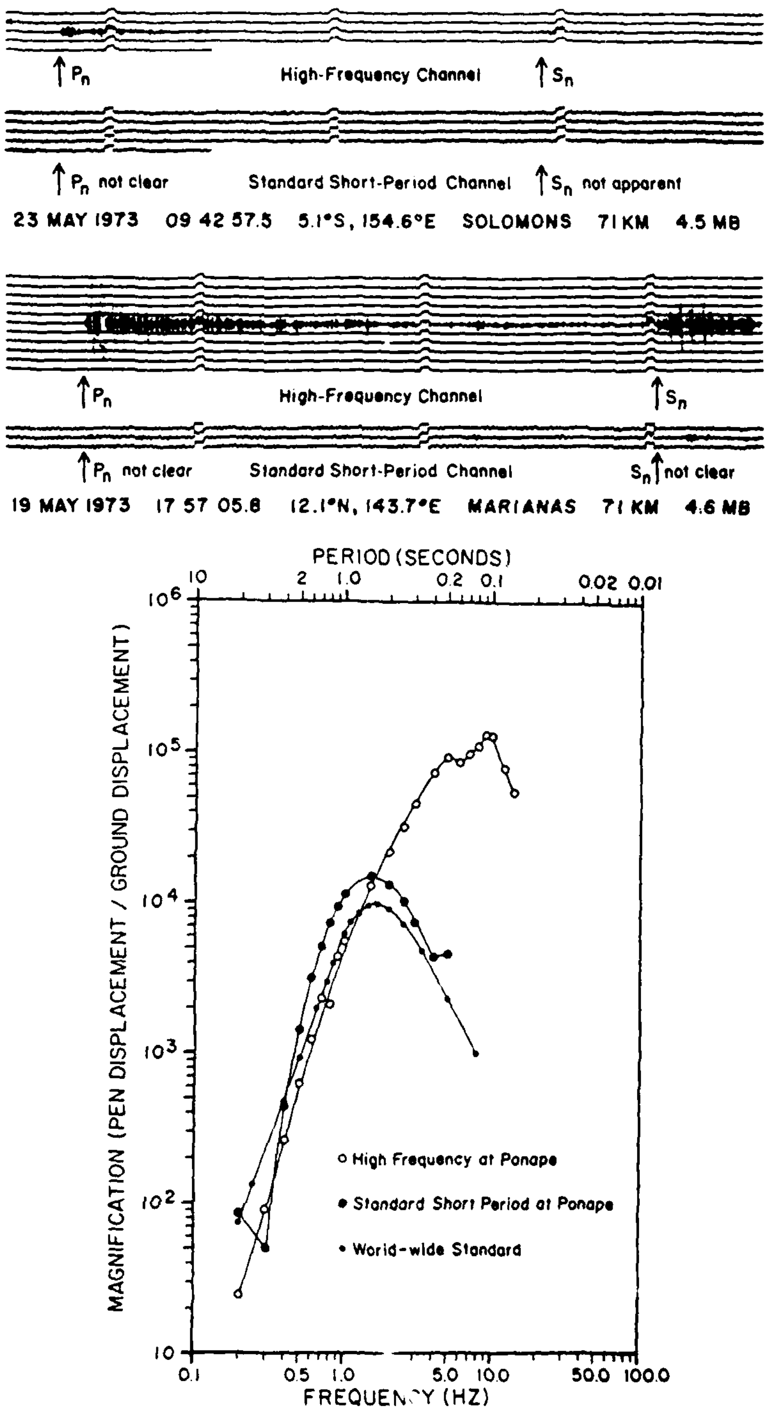

Figure 12. High-frequency P_n and S_n phases observed on the standard short-period instruments (top two traces) and a special high-frequency instrument peaked at 10 Hz. While the standard short-period instruments show unclear P_n and S_n phases, the high-frequency channels show clear distinct arrivals. This indicates that the oceanic lithosphere has an extremely high Q (after Walker, 1977). Instrument responses are shown below.

mantle wave guides. According to most indications, this apparent Q also increases with frequency. In physical terms, this dependence on frequency may also involve the physical sizes of the inhomogeneities in the crust (1, 21, 3, 57, 62, 78). According to some researchers the regional differences in the apparent Q in the crust discussed above may decrease with increasing frequency in such a manner that, at 25 Hz, all regions would have about the same apparent crustal Q_β (1).

In spite of the similarities in the regional frequency dependence of mantle and crustal Q_β, there need be no causal correlation between the two.

The physical processes causing the attenuation in the crust may be quite unrelated, and the general mobility of the low mantle regions and the associated inhomogeneity of the crust resulting from tectonic processes give rise to two quite unrelated dissipation mechanisms.

In the case of the dissipation of S_n and P_n, though, there may be a direct link between the two (4, 65). In both cases, such variations of dissipation with frequency, if universally present, facilitate the detection of high frequency energy at both teleseismic and regional distances.

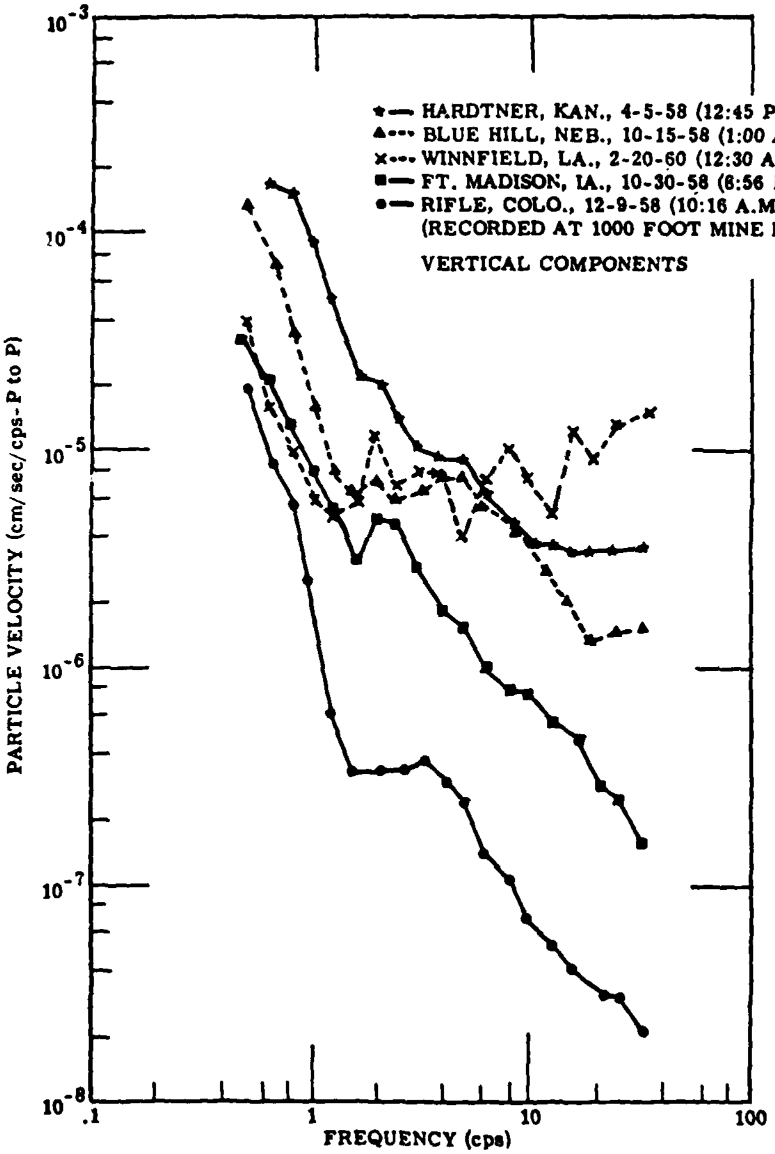

Figure 13. Earth noise spectra for five scattered continental interior sites in the United States (after Frantti, 1963c).

EXISTING DATA BASES FOR THE STUDY OF HIGH FREQUENCY GENERATION AND PROPAGATION IN THE 3 TO 10 HZ SEISMIC BAND

There exist several major data bases at Geotech that are suitable for the study of high frequency energy in seismic events. In the following, some of these are listed with the description of data quality and frequency content.

LRSM

The LRSM network consisted of a large number (ranging from 40 to 4 at various times between 1962 and 1970) of mobile seismic stations, located mostly in the contiguous United States. The peak response of the instrumentation is in the 3 to 4 Hz range. The analog tapes originally recorded were time compressed such that high frequency information was lost beyond about 7 Hz. In spite of this, this data base recorded on analog tapes, is extremely useful for seismic waves up to 7 Hz. A full day's data for all known nuclear explosions (US, USSR, French) was retained without data compression. Spectra of seismograms in the EUS often show a S/N ratio > 1 at 10 Hz at distances of 10°-15°.

The LRSM network is unique in its wide coverage of the continental United States. The dense areal coverage and the variety of the geological structures the sites cover make it eminently suitable for re-studying propagation effects on regional phases. No other network has the coverage to follow the regional high frequency phases over long paths and study the progressive changes in characteristics brought about by scattering and Q.

SDCS

The SDCS network, consisting of a combination of analog and digitally recording seismic stations, was operational in the time span of 1975 to 1979. The digital data sampled at 20 Hz is suitable for analysis of seismic frequencies up to near 10 Hz. The stations were located in the continental U.S. and Canada. A considerable amount of work has already been done on these data. Although of high quality, the sparse areal coverage of this network is a drawback.

VELA Observatories

Like the LRSM data, the data at these observatories, CPO, BMO, TFO, WMO and UBO are suitable for the analyses of high frequency seismic signals at least up to 7 Hz. These observatories were operational concurrently with the LRSM system. In addition to the normal SP instrumentation, but for a limited period of time, special channels with response peaked at 6 to 10 Hz were also operated at these arrays. The data from these channels was recorded on film and analog tape. The system noise on some of these recordings is quite high, but on occasion the systems detect seismic energy up to 15 Hz at epicentral distances of 5° to 9°.

TFO is unique among the arrays of the world because an array of three-component sensors was operated there for a period of time. This makes this array eminently suitable for studying modal characteristics and particle motion of regional phases of both P-SV and SH type. Phase velocity measurements can also be done efficiently on this array.

The use of the LRSM and VELA array data was severely restricted in the past by the lack of suitable A/D equipment. The recent acquisition of new equipment largely reduces the problem and we expect that these data bases will make a significant contribution to the study of high frequency seismic energy in the future.

SRO Stations

The SRO network data is nominally suitable for the recording of data up to 10 Hz on the vertical component. In regions of high to moderate seismicity, a sufficient amount of data is available for data analysis of high frequency energy. At some locations, however, we found that there is a lack of suitable data, due to the fact that the recording system does not trigger for many local or regional events, and the recording stops before some portions of the records of interest, such as the L_g codas, are fully recorded.

LASA and NORSAR

In spite of the long operational life of these arrays, emphasis on teleseismic events resulted in a retention policy such that most local and regional events were discarded. Continuous data exists for only a few limited time windows. There is a large data base for teleseisms, on the other hand. At NORSAR, more of the regional events were retained on the initiative of the scientists running the array. The new high sensor density-high frequency subarray is at present producing data that is available to the scientific community.

NSS

The National Seismic Station, the prototype for a CTB monitoring station, was set up at CPO and operated between March and July 1979. The high frequency channel peaked around 10 Hz and is suitable for the analysis of a few local and regional events. Unfortunately, system problems occurred repeatedly during most of the operational life of this station and only a few usable events could be recovered.

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II STUDIES OF RADIATION FROM HIGH-EXPLOSIVE AND NUCLEAR CRATERING EVENTS

INTRODUCTION

Rygg (1979) noted polarity reversals for LR from some Soviet explosions. Model studies of explosion-generated Rayleigh waves by Gupta and Kisslinger et al (1964) and field studies of SH motion from explosion by Kisslinger et al (1961) suggest that such observations can be explained by a near-surface explosion. To further explore this possibility we have:

- Conducted telephone interviews with persons expert in the field of buried explosions to discuss sources of relevant data. Further work in literature review and gathering data along these lines was not performed, at the request of the project officer.

- Reviewed the rock mechanics literature, e.g., International Journal of Rock Mechanics, for relevant papers and found very little of relevance.

- Established that LR waveshapes overlay for cratering and contained shots, while the LQ varies dramatically from event to event even within each category, and that, for events of the same frequency distribution, cratering, contained, and collapsed P waves show the same initial polarity. Events analyzed include HAYMAKER, PALAQUIN, SEDAN and collapses from DUMONT and PIRHANA.

SOURCES OF CRATERING DATA FROM DETONATIONS OF BURIED HIGH EXPLOSIVES

Persons interviewed were:

Andre S. Kusubov
Dr. Theile (AFWL)
Brian Stump (AFWL)
Tom McEvilly (Berkeley)
Otto Nuttli (St. Louis University)
Leslie Hill (Sandia)
Robert Massé (AFTAC)
James Drake (Waterways Experiment Station)
Dr. Henny (AF)

An attempt was made to contact Doris Tendall at Sandia; however, she had retired.

Valuable information was gathered from James Drake, Leslie Hill and Andre S. Kusubov.

James Drake (July 14, 1980)

As a general remark, Drake stated that there has been very little transverse data taken. However, the Jangle H.R. series and the Teapot-S nuclear shot data are being reduced by Scott Blouin of Applied Research Associates in S. Royalton, Vermont and there may be transverse data there. The series is in soil from near-surface to buried.

Another shot for which there is poor close-in transverse data taken by Waterways is Pre Gondola set off in clay and shale. LLL has some "far out" data.

UET high explosive (H.E.) tests in the 1940's were carried out by the San Francisco Corps of Engineers and the Waterways. There were detonations, from 300 lbs. to 320K-lbs., some contained, in soil, granite, sandstone, lakebed, etc. Raw data probably does not exist--only reports which can be read in Drake's library and ordered through DDC.

The "MOLE" series was in the early 1950's; it was for explosions of < 2000 lbs. H.E. in soil in Oklahoma and Mississippi. Stanford Research Institute wrote reports--available at Drake's library.

Sandia made measurements of "Air Vent" and "Scooter" 100K lbs. at 100' in alluvium. Data was taken at 100' intervals; Perret has this data. "Air Vent" was one 20-ton shot. A relevant report is by Paul Kintzinger, October 1964, Sandia Report SCRR64549.

Work of interest was performed when it was thought that a new Panama Canal might be dug using nuclear explosives. The Essex series was detonated in soil at or below the water table, in the late 1960's and early 1970's in Ft. Polk, Louisiana under the control of the Waterways Experiment Station. The size of shots was 10 tons. Some analog data may be available.

There was a small test series called CENSE, using charges of 300-1000 lbs. explosives at depths ranging from the surface to semi-contained. There are two reports NT-N-77-6, The CENSE Experiment Test Program. Part I was for explosions in rock and sandstone, and Part II for explosions in soils. The time function for the P wave in soil was 10-20 times longer than for in rock; the particle velocity was higher in rock. Even in hard rock, there was very little change in amplitude of cube-root scaled amplitude as one went from contained to cratering explosions.

An important series of papers that form a review of ground motion, drawing on USGS and Russian data, was published by Hank F. Cooper of R and D Associates of Rosslyn (reports TR-1062, 063, 077)-DNA.

A good source for viewing many of these reports is the Waterways Library.

Leslie Hill (July 18, 1980)

The Buckboard and Pre-Schooner shots were about 20 tons in basalt. Information may be found in PNE Reports. See also the Plowshare bibliography obtainable from NEIS TID 3522, 9th revision.

Andre S. Kububov

In 1973- 74, there was an extensive experimental program on the order of 200 buried and surface H.E. explosions ranging from 50 grams to 100 lbs. at Yucca Lake at NTS. The shot points varied in depth from the surface and 2 foot depths to a depth of 50 feet. Data was gathered typically on 30 channels, including several 3-component sets. Several of the shot holes were excavated after the shots and photographs were taken, showing cracks and explosion-created asymmetrical cavities. The data exist in the forms of analog and digital tape and also as photographic records of plots.

The data have never been analyzed on anything like the scale justified by the expense taken in obtaining the data. The data were gathered for the purpose of studying enhanced generation of shear waves from multiple shots and from shots detonated at different depths; and the experimental design was aided by H. Rodean, W. Hannon, D. Larson, P. Roger, and T. McEvilly. Relevant refereces are by Kusubov (1976, 1978).

SELECTED REFERENCES

Kusubov, A. S. (1976). Surface and body waves from surface and underground explosions, VCID-17222, Lawrence Livermore Laboratories, Livermore, California.

Kusubov, A. S. (1978). The design and execution of the Rayleigh wave experimental program at Yucca Lake, Nevada VCRL-52446, Lawrence Livermore Laboratories, Livermore, California.

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